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STUDIES FOR DETERMINING THE OPTIMUM PROPULSION SYSTEM CHARACTERISTICS FOR USE IN A LONG RANGE TRANSPORT AIRCRAFT

by

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PRATT & WHITNEY AIRCRAFT
DIVISION OF
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prepared for

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16. Abstract

A comprehensive evaluation of propulsion systems for the next generation of near-sonic long-range transport aircraft indicates that socially responsive noise and emission goals can be achieved within the probable limits of acceptable airplane performance and economics. Technology advances needed in the 1975-1985 time period to support the development of these propulsion systems are identified and discussed. The single most significant result is the low noise, high performance potential of a low tip speed, spaced, two-stage fan.

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FOREWORD

The work described herein, which was conducted by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, was performed under NASA Project Manager, Mr. John H. Povolny and Technical Coordinator, Mr. Robert J. Antl, Airbreathing Engines Division, NASA-Lewis Research Center. The report was prepared by G. A. Champagne, R. B. Dyson, W. W. Ferguson and R. A. Howlett under the direction of G. L. Brines, the Pratt & Whitney Aircraft Program Manager.

The provisions of NASA Policy Directive (NPD) 2220.4, dated May 15, 1970, subject: Use of International System of Units (SI) in NASA Publications, have been waived under authority of subparagraph 5.5, NPD 2220.4.

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SUMMARY

The propulsion study described in this report has had three primary objectives:

- Evaluate Advanced Technology Transport engine cycles which meet future noise and emission goals with minimum system penalty.
- Evaluate the impact of advanced propulsion technology on noise, emissions, performance and the overall system.
- Recommend to NASA the necessary programs to acquire this technology.

Extensive parametric cycle studies showed that a twin spool turbofan engine with a low tip speed, widely-spaced two-stage fan is best able to meet the primary design criteria of low noise and low emission levels with minimum penalty.

The noise goals of FAR Part 36 minus 10 EPNdB for 1979 commercial service and FAR Part 36 minus 15 EPNdB for 1985 can be met with cycles using this new two-stage fan in combination with extensive advanced acoustic treatment in the nacelle. Aircraft operating procedures for noise abatement during approach and climb-out after take-off also offer important noise reduction potential. As engine associated noise is reduced airframe generated noise may become controlling.

An advanced two-zone combustor will reduce all emissions to levels below those set as study goals, except for nitric oxide. This emission is reduced by one-half from the level of today's high pressure ratio engines and will require some water injection to meet desired levels.

Several design innovations associated with this new engine require advanced development. These include:

- Low tip speed, two-stage spaced fan
- Low-speed, high work turbine
- Integrated engine/nacelle
- Advanced engine controls
- Low emission burner

Advanced materials offer important improvements in engine performance and weight. Significant new materials are:

- Graphite/epoxy for fan blades
- Ceramics for high temperature turbines
- Dispersion strengthened cobalt turbine vane material

- Advanced coatings for these cobalt materials
- Directionally solidified eutectic turbine blade materials
- Advanced coatings for eutectic materials
- Improved high temperature turbine disk materials
- High yield strength titanium disk alloys
- High creep strength titanium disk alloys

INTRODUCTION

During the past decade a revolution has occurred in commercial air transportation. Today swift, convenient, safe and economical airline service is available to almost any region of the world. The long-range transport airplane has been the foundation of this system and has provided a worldwide example of U. S. Aerospace excellence and technical/economic success. The modern aircraft powerplant has played a major role in achieving this status.

Recognizing the vital part that the long-range airplane plays in world commerce, NASA is studying the application of advanced technologies to the next generation of long-range aircraft to assure that future designs will be fully responsive to national needs. This Advanced Transport Technology Program consists of a broad evaluation of the benefits of technology advances in aerodynamics, propulsion, structures, controls and avionics. This report describes propulsion system studies performed under the direction of the Lewis Research Center to support this overall objective. The Langley Research Center has directed parallel studies of the overall system and the airframe, including propulsion integration. Close coordination has been maintained with the Langley system study contractors during this propulsion system study.

In evaluating new airplanes, it is especially important to recognize that the general public, and particularly airport neighbors, want transport aircraft to be quiet and clean (low in emissions). They also want limitations of airport encroachment on the adjacent community. The propulsion system plays a dominant role in achieving these social objectives and for this reason first priority in this program was given to making the study engines quiet and clean. Improvements in engine performance, reliability/maintainability and economics were also achieved subject to first meeting these social goals.

The propulsion study summarized in this report has had three primary objectives.

- Evaluate engine cycles which meet future noise and emission goals with minimum system penalty.
- Evaluate the impact of advanced propulsion technology on noise, emissions, performance and the overall aircraft system.
- Recommend to NASA the necessary programs to acquire this technology.

To meet these objectives, the work was divided into three tasks as shown in Figure 1. Task I involved the evaluation of 240 parametric engines to help define an optimum propulsion system. This work supported the first objective. Task 2 consisted of a preliminary design and component substantiation study for two cycles selected on the basis of the Task I evaluation. The two selected engines, designated the STF429 (BPR = 4.5, OPR = 25, FPR = 2.03) and STF433 (BPR = 6.5, OPR = 25, FPR = 1.95), have commercial certification target dates of 1979 and 1985, respectively. Advanced technologies, appropriate for the certification dates selected, were incorporated in each engine. Results of Task 2 were the primary input to achieving the second objective. Task 3 effort comprised the identification and evaluation of advanced technology payoff in advanced propulsion systems and recommendations to NASA regarding future technology programs (Objective 3).

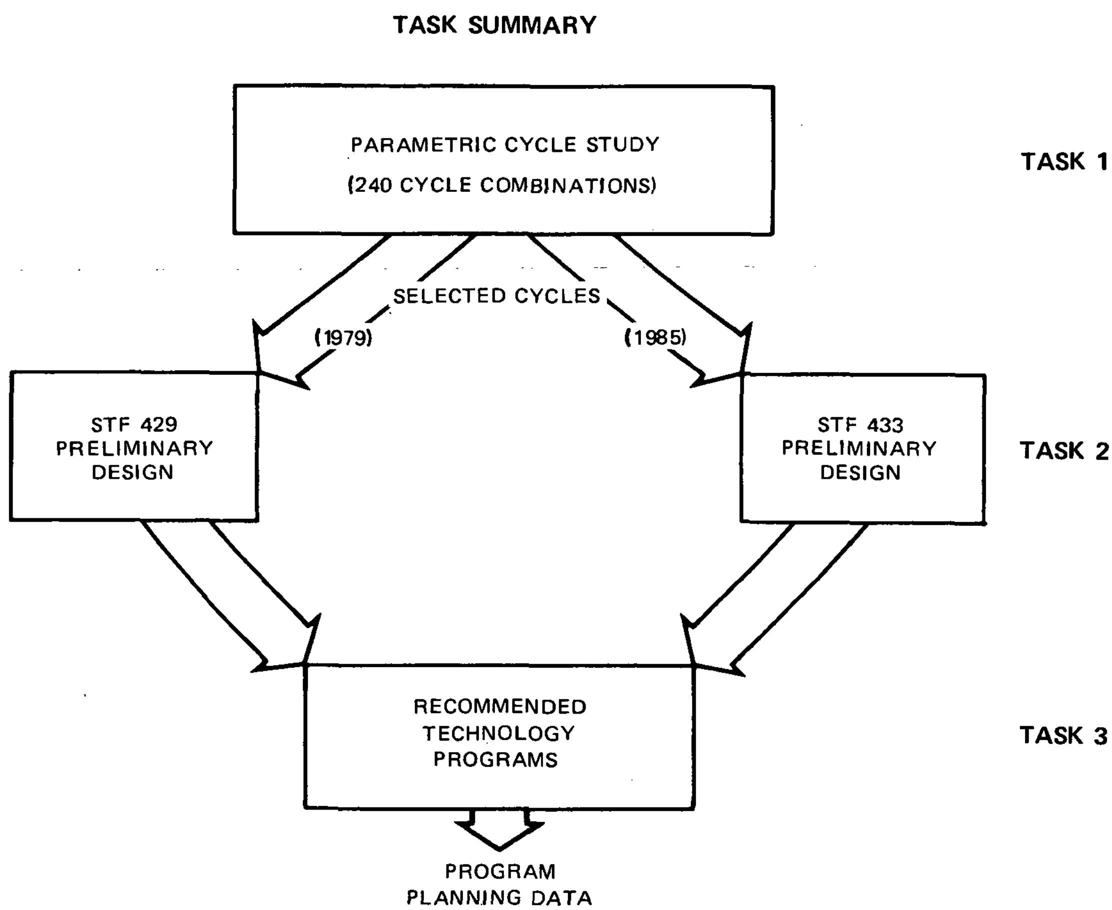

Figure 1 - ATT Program Tasks

A number of design features were incorporated in the two study engines which are very important in meeting the projected goals. The development of the low tip speed, spaced two-stage fan is particularly important in achieving the required fan pressure ratios of 1.95 and 2.03 and the noise goals with minimum system penalty. Attendant to this two-stage fan is the requirement for an efficient low-speed, high work turbine to drive it. Other component and system improvements which are important to an Advanced Technology Transport include an integrated engine/nacelle, advanced engine controls and variable engine geometry.

Improved materials were used throughout the study engines to improve performance and reduce weight. Development of these materials and techniques for their use in commercial production are required. Among the important development items are:

- Graphite/epoxy for fan blades
- Ceramics for high temperature turbines

- Dispersion strengthened cobalt turbine vane material
- Advanced coatings for these cobalt materials
- Directionally solidified eutectic turbine blade materials
- Advanced coatings for eutectic materials
- Improved high temperature turbine disk materials
- High yield strength titanium disk alloys
- High creep strength titanium disk alloys

TASK I

DISCUSSION

The objective of Task I was to determine the optimum propulsion system characteristics for an advanced technology, long range, commercial transport aircraft that employs supercritical wing technology to permit efficient flight near the speed of sound. Since these new aircraft must exhibit improved noise and emission characteristics, the Task I studies were directed toward the selection of those engine cycles which yielded low noise and emissions with minimum total aircraft system economic penalty.

Evaluation of the impact of current propulsion system technology and cycle variables on the total aircraft system economics were performed by using system modeling techniques. These techniques involve two major disciplines: (1) determining basic aircraft aerodynamic, weight, mission performance and resulting engine size and estimating the aircraft gross weight required to satisfy a specified payload/range requirement, and (2) estimating the economics of the resulting vehicle, considering the direct operating costs (DOC), indirect operating costs (IOC) and the total airplane investment. The net vehicle operating profit, which is the difference between the revenue obtained from flight operations and the sum of direct plus indirect costs, measured relative to the total airplane investment determines the return on the investment. This return-on-investment (ROI) is used as a measure of the economic worth (to an airline operator) of a proposed system change or technology advance. The direct and indirect operating cost categories used in this evaluation are as defined in the Civil Aeronautics Board Uniform System of Accounts and Reports.

The airplane used in the Task I evaluation is an advanced technology, three-engine aircraft which utilizes the results of recent developments in supercritical wing technology to provide a significant improvement in high-speed cruise performance. Its aerodynamic characteristics are based on wind tunnel tests conducted at the NASA Langley Research Center. The aircraft is designed to carry 200 passengers. The aircraft and mission ground rules used for the Task I propulsion evaluation studies are listed in Table I. The several noise and emission levels shown in Table II were established as system goals for the Task I evaluation. The ranges of engine cycle variables studied during Task I are presented in Table III. Close coordination and interchange of information was maintained with the airframe contractors participating in the NASA Langley sponsored "Study of the Application of Advanced Technologies to Long Range Transport Aircraft".

TABLE I

AIRCRAFT AND MISSION GROUND RULES FOR NASA HIGH PERFORMANCE CONFIGURATION

Design Range ~ n. mi. (km)	5500 (10200)	3000 (5556)
Cruise Mach Number	.97	.98
Initial Cruise Altitude ~ ft. (m)	36000 (10980)	38000 (11,600)
Takeoff Field Length @ 1000 ft. elevation (304.8 m), 90°F (305.5K)	10000 (3048)	8300 (2530)
Approach Speed ~ knots (m/sec)	145 (74.6)	135 (69.5)
Wing Loading ~ lbm/sq. ft. (kg/m^2)	140 (685)	120 (587)

TABLE II

NOISE AND EMISSION GOALS

Emissions	Goal	
Carbon Monoxide (CO) - At Idle	40	lb./1000 lb. m fuel (Kg/1000 Kg fuel)
Unburned Hydrocarbons (HC) - At Idle	8	
Nitric Oxides (NO) - At Takeoff	3	
Smoke - At Takeoff	SAE No. = 15 (Using SAE ARP 1179 Meas't Spec.)	

Noise Levels Considered

Federal Air Regulation, Part 36

1. Operation within the limits of FAR Part 36
2. Operation 10 EPN db below FAR Part 36
3. Operation 20 EPN db below FAR Part 36

TABLE III

RANGE OF ENGINE CYCLE VARIABLES STUDIED

Maximum Cruise Combustor Exit Temperature °F (K)	1800 - 2800	(1256 - 1810)
Overall Pressure Ratio (OPR)	15 - 40	
Bypass Ratio (BPR)	1 - 10	
Fan Pressure Ratio (FPR)	1.3 - 4.8	

RESULTS

The engine bypass ratio was the most critical parameter in selecting the optimum engine cycle. The results of the bypass ratio evaluation for aircraft design ranges of 5500 nautical miles (N. Mi.) (10200 km) and 3000 N. Mi. (5556 km) are plotted in Figure 2. They show that the bypass ratio for the 5500 N. Mi. (10200 km) design range aircraft should be between four and six while that for the 3000 N. Mi. (5556 km) design range aircraft should be somewhat lower (three to five). These bypass ratio results reflect the relative importance of nacelle weight, diameter (drag) and fuel consumption for the two design ranges.

The results of the cruise combustor exit temperature evaluation (Figure 3) show the optimum temperature to be in the region of 2200°F (1478K) to 2500°F (1643K) for the 5500 N. Mi. (10200 km) range and 2200°F (1478K) to 2700°F (1755K) for the 3000 N. Mi. (5556 km) range. As turbine temperature is increased, thrust per pound of airflow increases. Therefore, engine weight, diameter and drag will decrease for the same cruise thrust. At the same time, cruise fuel consumption tends to increase due to increased turbine cooling air requirements. The gross weight trends reflect the balancing effect of these factors for each range flown.

The overall pressure ratio (OPR) evaluation (Figure 4) shows the optimum overall pressure ratio to be approximately 30:1 for both design ranges. The sensitivity of the 3000 N. Mi. (5556 km) range aircraft to variations in overall pressure ratio is considerably less than that of the 5500 N. Mi. (10200 km) range aircraft due to the reduced emphasis on fuel consumption for the shorter range aircraft. Emission studies conducted during Task I indicated a significant increase in nitric oxide output as pressure ratio was increased. To maintain this emission at acceptable levels without water injection, it was necessary to select a somewhat lower (25:1) overall pressure level. Figure 4 shows that this choice results in only a small increase in aircraft design gross weight.

Extensive noise studies were conducted in Task I for untreated and acoustically treated nacelles. Noise levels were estimated based on present acoustic treatment technology. These studies indicated that for bypass ratios of four to five, FAR Part 36 minus 5 EPNdB could be obtained with a treated nacelle incorporating two inlet acoustic rings and one fan exhaust duct acoustic ring. Further noise reduction to FAR Part 36 minus 10 EPNdB and below would require a large increase in bypass ratio that would result in significant performance penalties to the overall aircraft performance.

Also during Task I, studies were conducted to identify potential advanced technology improvements in source noise reduction and more effective acoustic treatment. These technologies provide the potential for significant noise reduction and were incorporated into the two advanced technology engines studied in detail in Task II. These technology improvements are described under Task II (Impact of Advanced Technology).

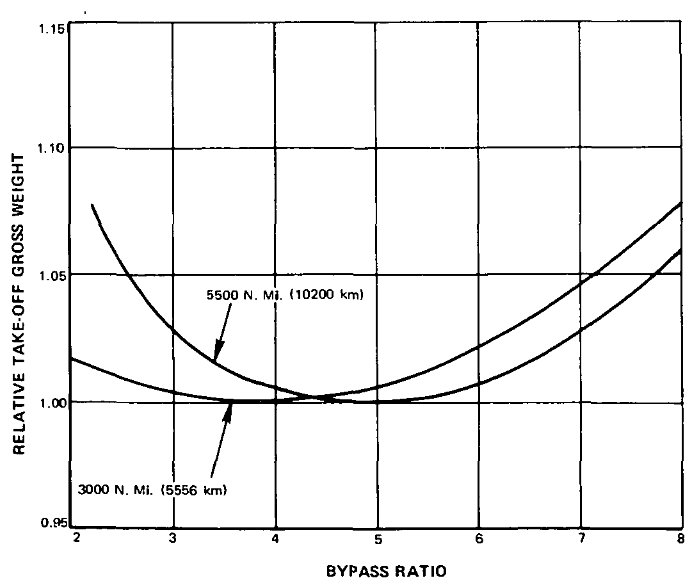

Figure 2 - Bypass Ratio Optimization

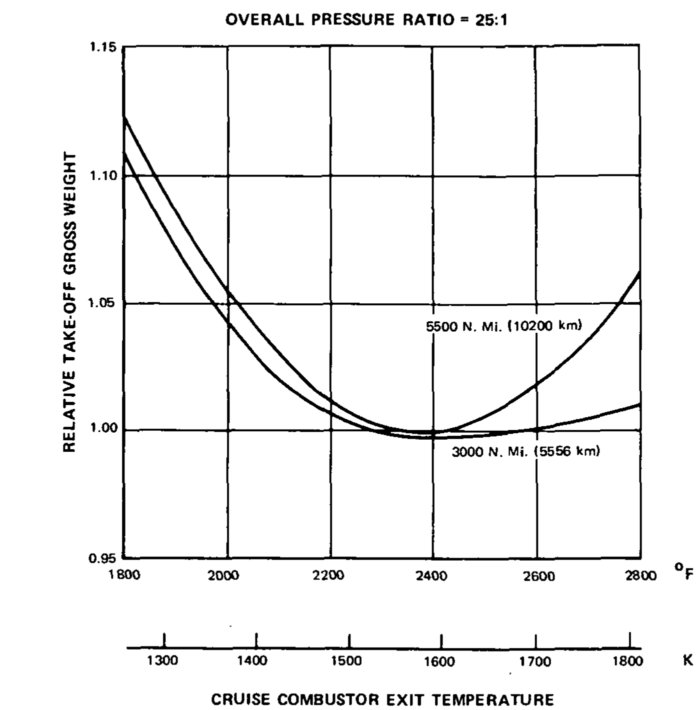

Figure 3 - Combustor Exit Temperature Optimization

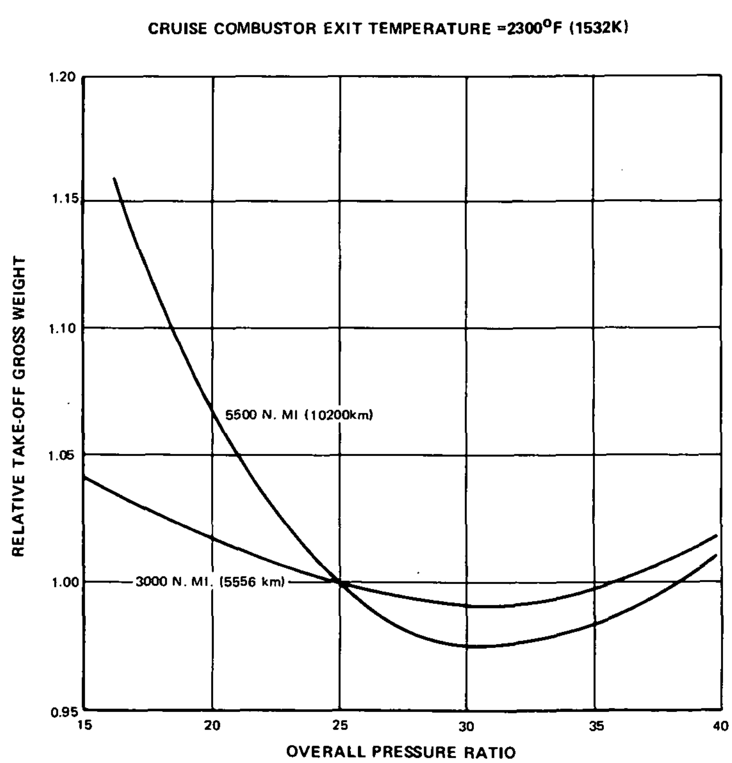

Figure 4 - Pressure Ratio Optimization

TASK II

OBJECTIVE

The Task II study involved the preliminary design of two advanced technology turbofan engines to meet the noise and certification requirements outlined in Table IV with minimum aircraft economic penalties. The Task I cycle studies served as the basis for selecting these engines. Each was optimized to power a three-engine aircraft designed to carry 200 passengers 3,000 N. Mi. (5556 Km).

TABLE IV

ENGINE REQUIREMENTS

Commercial Certification Date	1979	1985
Treated Minimum Noise Level	FAR-10 EPNdB	FAR-15 EPNdB
Noise Goal, Operating Procedures		FAR-20 EPNdB
Number of Fan Stages	2	Optional
Cruise Mach Number	0.98	0.95

CYCLE SELECTION

Selection of the specific engine cycle characteristics for these two engines included consideration of the following:

- Aircraft Performance
- Noise Goals
- Low Emission Levels
- Advanced Technology Forecasts
- Fan Stage Requirements

COMBUSTOR EXIT TEMPERATURE

Task II studies verified the Task I results that aircraft performance for the 3000 (5556 Km) airplane is near-optimum for a range of design cruise combustor exit temperatures (CET) from 2200°F (1478K) to 2700°F (1755K). The selected CET for the 1979 and 1985 engines fall within this range. Maximum engine operating temperatures for these engines were selected from CET forecasts for commercial engine service in 1979 and 1985.

OVERALL ENGINE PRESSURE RATIO

Task II studies re-confirmed that aircraft performance is best at an engine overall pressure ratio (OPR) of about 30, while emission considerations require the lowest possible burner inlet pressure and temperature to meet the NO emission goal. A trade-off between these conflicting requirements shows that reduction of OPR to 25 will provide a 20 percent reduction in NO emissions and a one percent increase in aircraft gross weight. Reducing OPR below this value will produce significant aircraft penalties and for this reason, an OPR of 25 was selected for both the 1979 and 1985 engines.

BYPASS RATIO – FAN PRESSURE RATIO

The bypass ratios and fan pressure ratios for the 1979 and 1985 engines were selected to produce the specified noise levels with minimum aircraft economic and weight penalties. The following sections outline the acoustic technology advancements forecasted for 1979 and 1985, and show how these projected improvements were used in selecting the final bypass ratios and fan configurations for the two engines studied.

ACOUSTIC TECHNOLOGY

The Task I studies confirmed that significant improvements in current acoustic treatment technology are needed to reach the 1979 and 1985 noise goals using engine cycles that will result in reasonable levels of airplane gross weight, DOC and ROI. A continued high level of noise research is expected to yield significant improvements in acoustic technology.

Improved acoustic material effectiveness will occur in the form of increased peak attenuation, broader band width and reduced weight penalties. Improvements in band width and peak attenuation assumed in this study are shown in Figure 5. These improvements could result from (1) the use of multilayer, multi-degree of freedom treatment designs to make the treatment effective over a wider bandwidth, (2) tailoring treatment design along the length of the duct to match the varying environmental conditions that exist along the duct passage to improve peak attenuation, and (3) development of improved, lighter weight materials.

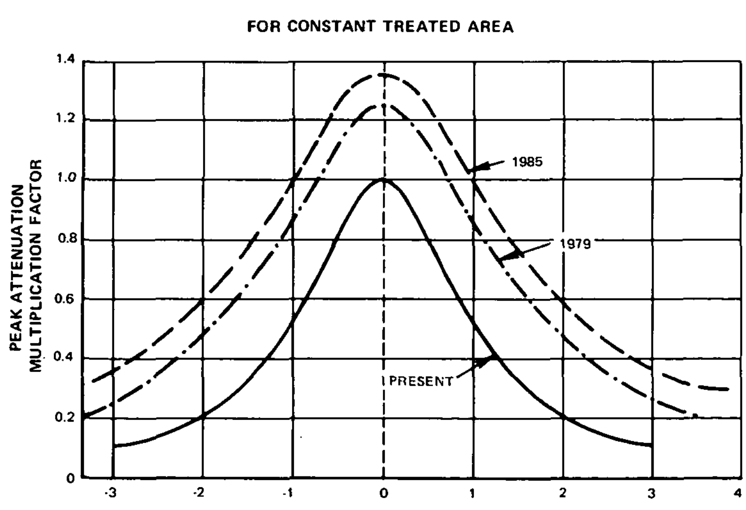

Figure 5 - Assumed Improvements in Band Width and Peak Attenuation

Jet noise levels at velocities below 1000 feet per second (304.8 m/sec) play a significant role in determining total engine noise levels. Figure 6 shows the jet noise improvements expected as additional research provides a better understanding of the mechanism and control of this noise source.

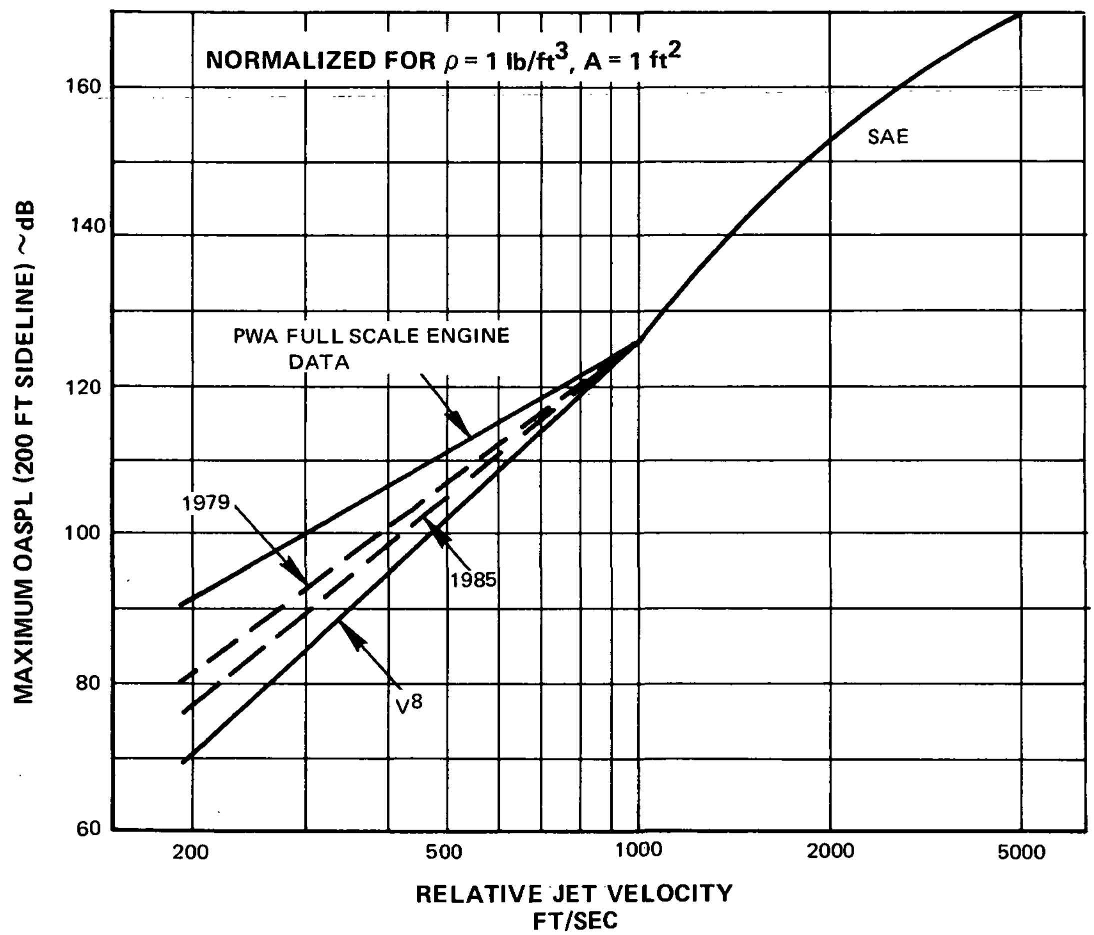

Figure 6 - Jet Noise Improvements as a Function of Jet Velocity

BYPASS RATIO – FAN SELECTION

Table V shows the Task II estimates of untreated and treated approach and sideline noise levels for cycles using the acoustic advancements forecast for 1979. With untreated nacelles, the present FAR Part 36 noise level of 106 EPNdB can be met with a near optimum 5.5 BPR two stage fan and a compromised 7.5 BPR single stage fan.

TABLE V

1979 ACOUSTIC TECHNOLOGY SUMMARY

			APPROACH - 370 ft (113 m)		SIDELINE - .25 N.Mi (463 m)	
Number of Fan Stages	Design BPR	Design FPR	Untreated Total Noise EPNdB	Treated Total Noise EPNdB	Untreated Total Noise EPNdB	Treated Total Noise EPNdB
2	3	2.39	113	99	110	101*
2	4	2.11	111	97	109	97*
2	5	1.91	107	93	108	94
2	6	1.78	103	89	105	90
1	5	1.70	110	96	110	102*
1	6.5	1.70	109	95	108	93
1	8	1.58	105	92	105	91

*Treatment Noise Reduction Limited by Jet Noise Level

In order to achieve the 1979 noise goal which is equivalent to 96 EPNdB at approach and sideline, either a 4.5 BPR, two-stage fan or a 5.5 BPR, single stage fan is required. A system evaluation showed that the 4.5 BPR two-stage fan engine will have a lower gross weight than the single stage system. The fan pressure ratio required for optimum cruise performance for the 4.5 bypass ratio cycle is 2.03. The fan tip speed required for a two-stage fan is 1270 feet per second (387 m/sec). To achieve a fan pressure ratio of 1.9 with a single stage fan would require tip speeds greater than 1800 feet per second (549 m/sec). Therefore, the single stage fan would have a higher cruise fuel consumption due to the non-optimum fan pressure ratio (1.9 versus 2.0) and poorer fan efficiency due to the high tip speed. The higher relative tip speed will also result in higher noise at both take-off and approach power. These data verified that a low tip speed, spaced, two-stage fan was the best choice for the 1979 engine designated the STF429.

A similar fan/acoustic evaluation was performed assuming 1985 technology levels. Results indicated that either a 6.5 BPR two-stage fan or an 8.0 BPR single stage fan would achieve a treated noise level of 91 EPNdB at approach and sideline which correspond to the -15 EPNdB goal set for this time period. An aircraft economic evaluation of these cycles showed the low tip speed two-stage fan (STF433) to be the better choice.

SELECTED CYCLES

Table VI presents the two selected cycles.

TABLE VI

SELECTED CYCLES

	STF429 (1979)	STF433 (1985)
Design Bypass Ratio	4.5	6.5
Design Overall Pressure Ratio	25	25
Design Fan Pressure Ratio	2.03	1.95
Number of Stages	2	2

NOISE

Estimated noise levels for the STF429 and STF433 engines are shown in Figures 7 and 8. With extensive nacelle treatment the STF429 meets its -10 EPNdB noise goal. Similarly, the STF433 meets its -15 EPNdB noise goal at all three noise measurement conditions. The top of the bar graphs indicate the untreated noise level. The cross-hatch area illustrates the noise reduction due to the acoustic treatment in the nacelle (wall plus two inlet rings and one fan duct splitter). Total jet noise level is also indicated.

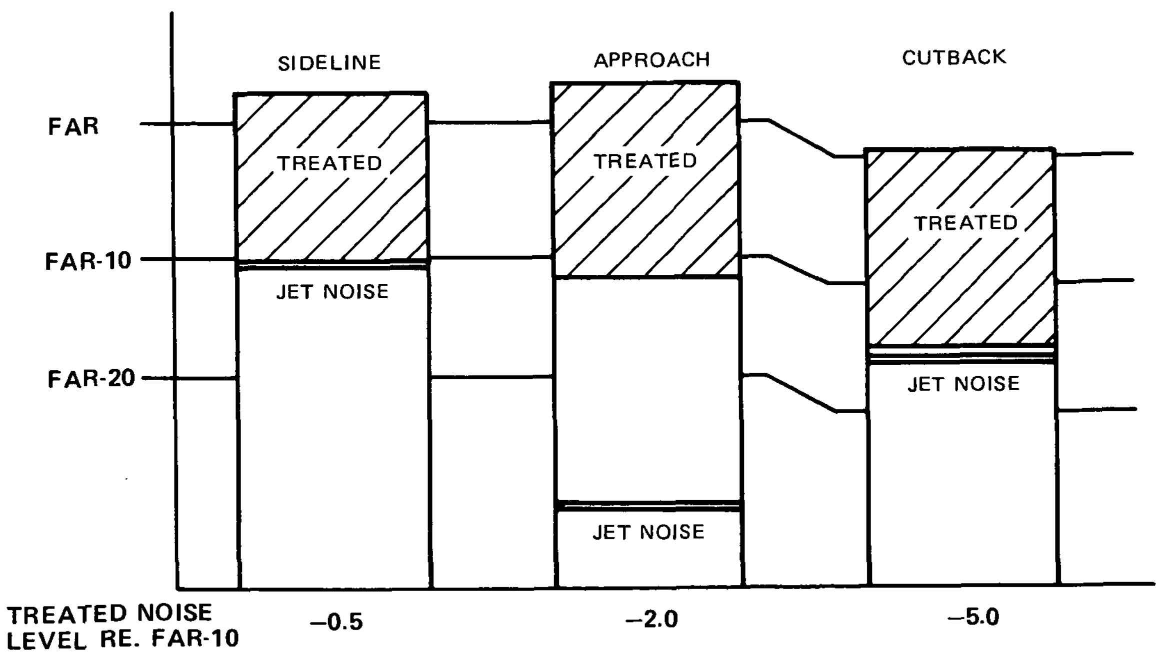

Figure 7 - Estimated Noise Levels for Three STF429 Engines

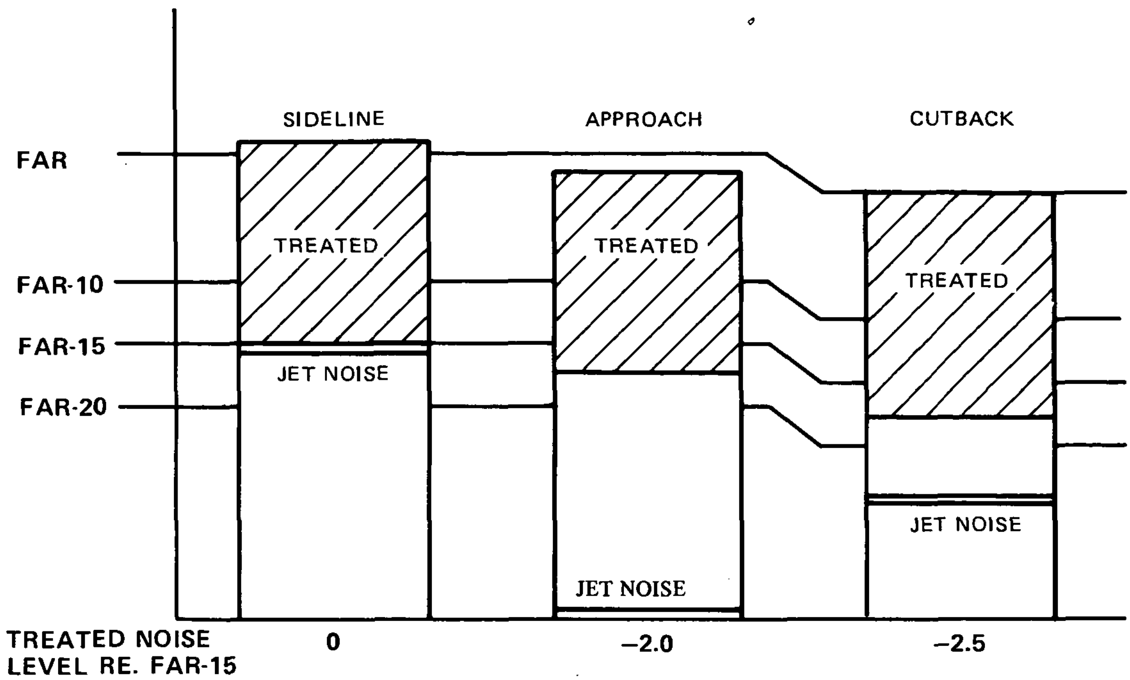

Figure 8 - Estimated Noise Levels for Three STF433 Engines

COMPONENT DESIGN

For the preliminary design study of these engines, areas of advanced technology were projected on a basis that is consistent with the certification dates for each engine. A five year period was allowed between technology demonstration and engine certification. In selecting appropriate areas of advanced technology, prime consideration was given to reducing noise and emission levels. Other technology decisions were based on the sensitivity of near-sonic, long range transports to engine cruise performance (thrust specific fuel consumption and thrust per unit of airflow), engine weight and engine cost.

Each engine has a low tip speed, two-stage fan which is driven by a highly loaded turbine. Figure 9 shows the basic characteristics of this low noise fan design. Composite fan blades are projected for both engines. The tip speed of the first stage is about 50 percent lower than a single stage fan that provides the same fan pressure ratio. The number of blades and stators in each row was selected to avoid discrete blade passing frequencies and harmonics. A further noise reduction feature is the greater than 200 percent axial tip spacing between the rows of airfoils. This spacing allows the wake from each row of airfoils to attenuate before reaching the downstream row of airfoils. In addition to these low-noise features, the fan has a high efficiency because of the low tip speed.

To compliment this low-noise fan, the fan drive turbine for each engine is a highly loaded, low speed design with high efficiency. The envelope diameters of these turbines are consistent with the dimensions set by the fan in order to eliminate installation penalties resulting from a large diameter turbine.

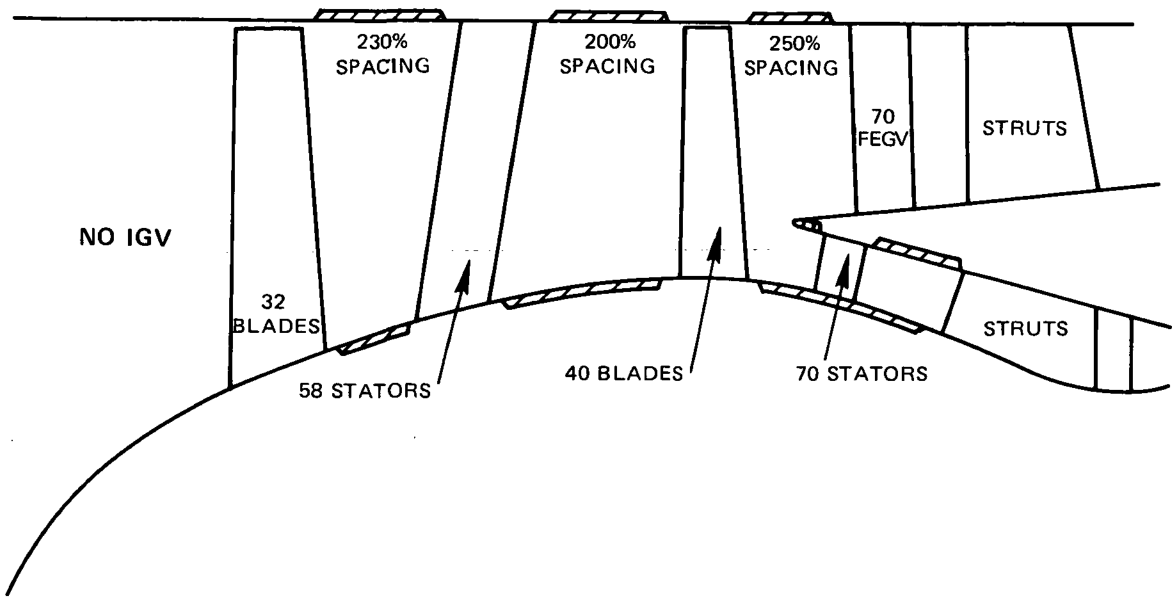

Figure 9 - Flow Path for the Low-Noise Fan Design

The advanced burner design for each engine combines several features that reduce exhaust emission levels without sacrificing burner performance or altitude relight capability. These features are:

- Premixing the fuel and air prior to combustion
- Designing the primary zone for lean combustion
- Staging the fuel flow for improved combustion efficiency
- Providing a high fuel source density

The first two features reduce nitric oxide (NO) concentrations in the exhaust gas at maximum power generation. This is accomplished by reducing the residence time of air in the peak temperature zone and also by lowering the peak flame temperature. The third feature reduces the formation of carbon monoxide and unburned hydrocarbons at low power operation including ground idle. This is obtained by staging the fuel flow into two zones. One zone, the pilot, is designed for low power operation and operates at all power settings. The second zone operates at intermediate to maximum power levels. This staged burner design improves burner efficiency at off-design operation, especially at very low power levels, and thereby reduces carbon monoxide and unburned hydrocarbon concentrations. The last feature, a high density of fuel sources, provides more uniform fuel-air mixtures so that smoke and unburned hydrocarbon levels are reduced.

The more advanced burner for the 1985 certification date achieves further emission reductions by improving fuel preparation and injection techniques which reduce the fuel droplet size. Also, additional staging to reduce the recirculation residence time in the hot zone reduces NO levels.

Advanced technology for the high spool design of each engine (compressor and high pressure turbine that drives the compressor) was selected for high performance. Because turbine cooling air significantly affects engine performance, advanced technology to reduce cooling air requirements is especially beneficial. Consequently, advanced high temperature turbine airfoil materials and multi-hole film cooling techniques provide a significant improvement to the performance of both engines. Other areas of advanced technology are incorporated to reduce the high spool weight and cost while maintaining high performance for the compressor and turbine, including advanced disk materials, higher rotational speeds, increased aerodynamic loadings and optimum compressor configurations. These advancements enable reducing the number of compressor and turbine stages (savings in cost and weight) that are required to provide the overall pressure ratio.

A design study of the two engines in acoustically treated nacelles was accomplished during Task II. Figure 10 shows the basic features of these nacelles. Acoustic treatment consisted of two rings in the inlet, one in the fan duct and extensive wall lining in the fan inlet, the fan duct and the engine exhaust duct. The rings for the fan inlet require anti-icing and must have high resistance to foreign object damage. A variable lip is required to meet the contrasting conditions of a high fineness ratio for the nacelle lip at cruise and a liberal radius for low speed operation. To avoid a penalty in nacelle diameter (drag) and also to improve failure characteristics in the event of a wheels-up landing, the accessories are packaged both around the engine core and in a canoe-shaped fairing located in the fan duct rather than at the bottom of the nacelle. The fan thrust reverser and engine thrust spoiler are both cascade configurations arranged to provide a tight wrap around the engine, to be compatible with the acoustic treatment, and to provide good reversing effectiveness at low ground speeds. All of these nacelle features can be accomplished without reducing system maintainability by segmenting the nacelle components into modules which, when swung open, expose the engine and accessories for inspection servicing.

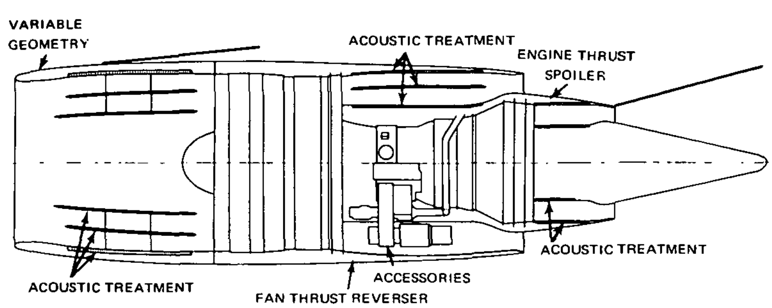

Figure 10 - Installation Sketch of the STF429 Engine

PRELIMINARY ENGINE SPECIFICATIONS

The estimated performance, weight and dimensions for the two study engines are shown in Table VII. Data are for the basic size engines, excluding acoustic treatment weight and installation losses. The engines are scalable to specific application requirements. For example, the engine sizes required for the 3000 n. mile (5556 km) range transport with full acoustic treatment shown in Figure 12, Page 22 is 36,400 lbf. (162,000 N) for the STF429 and 39,100 lbf (174,000 N) for the STF433.

TABLE VII

PRELIMINARY ENGINE SPECIFICATIONS

	STF429		STF433	
Design Cruise Thrust, lbf (N)	9130	(40550)	9501	(42200)
Design Cruise TSFC, lbm/hr-lbs (g/sec-N)	0.699	(0.01985)	0.684	(0.0194)
Design Corrected Airflow, lbm/sec (kg/sec)	1193	(541)	1375	(624)
Take-off Static Thrust, lbs (N)	41300	(183500)	41900	(186000)
Fan Tip Diameter, in, (m)	78	(1.98)	84	(2.135)
Maximum Diameter, in, (m)	81	(2.06)	86	(2.18)
Overall Length, in, (m)	140	(3.55)	140	(3.55)
Engine Weight, lbm (kg)	7250	(3280)	7330	(3320)

OPERATIONAL PROCEDURES FOR REDUCED NOISE

Various operational procedures were considered for the reduction of aircraft noise. The major factor involved in the majority of the operational procedures was the reduction in thrust required, thereby resulting in reduced noise.

Increasing the glide slope angle from the customary three degrees (.052 radians) to six degrees (.105 radians) reduces the normal approach power by one-half. This technique may be applied to either the two segment or the single segment approach and can reduce approach noise levels between seven and thirteen EPNdB, respectively. The two segment approach includes a transition from six degrees (.105 radians) to three degrees (.052 radians) approximately one nautical mile (1.853 km) from the runway threshold, whereas, the single segment approach maintains a constant six degrees (.105 radians) to the runway.

Increased approach speed will permit the use of lower flap settings which will also reduce noise by lowering approach power setting. This occurs because at reduced approach flap settings, the aircraft lift-drag ratio is improved and, therefore, less thrust is needed to maintain the desired flight path. A ten knot (5.14 m/sec) increase in approach speed, for example, results in a five EPNdB reduction in approach noise.

Approach noise can also be reduced by decreasing wing loading (larger wing area). The noise reduction obtained from the use of a 10 percent lower wing loading is approximately 3.5 EPNdB.

Cut-back noise can be reduced by using automatic flap retraction after take-off. The early retraction of flaps after take-off reduces the thrust required at cut-back by improving the aircraft lift/drag ratio. In using early flap retraction the aircraft gains a slightly increased altitude at cut-back but, more importantly, an improved lift/drag ratio. The resulting noise reduction at the 3.5 N.Mi (6.49 km) noise measuring station is approximately three EPNdB.

A summary of the noise reductions obtained from the use of operational procedures is shown in Figure 11.

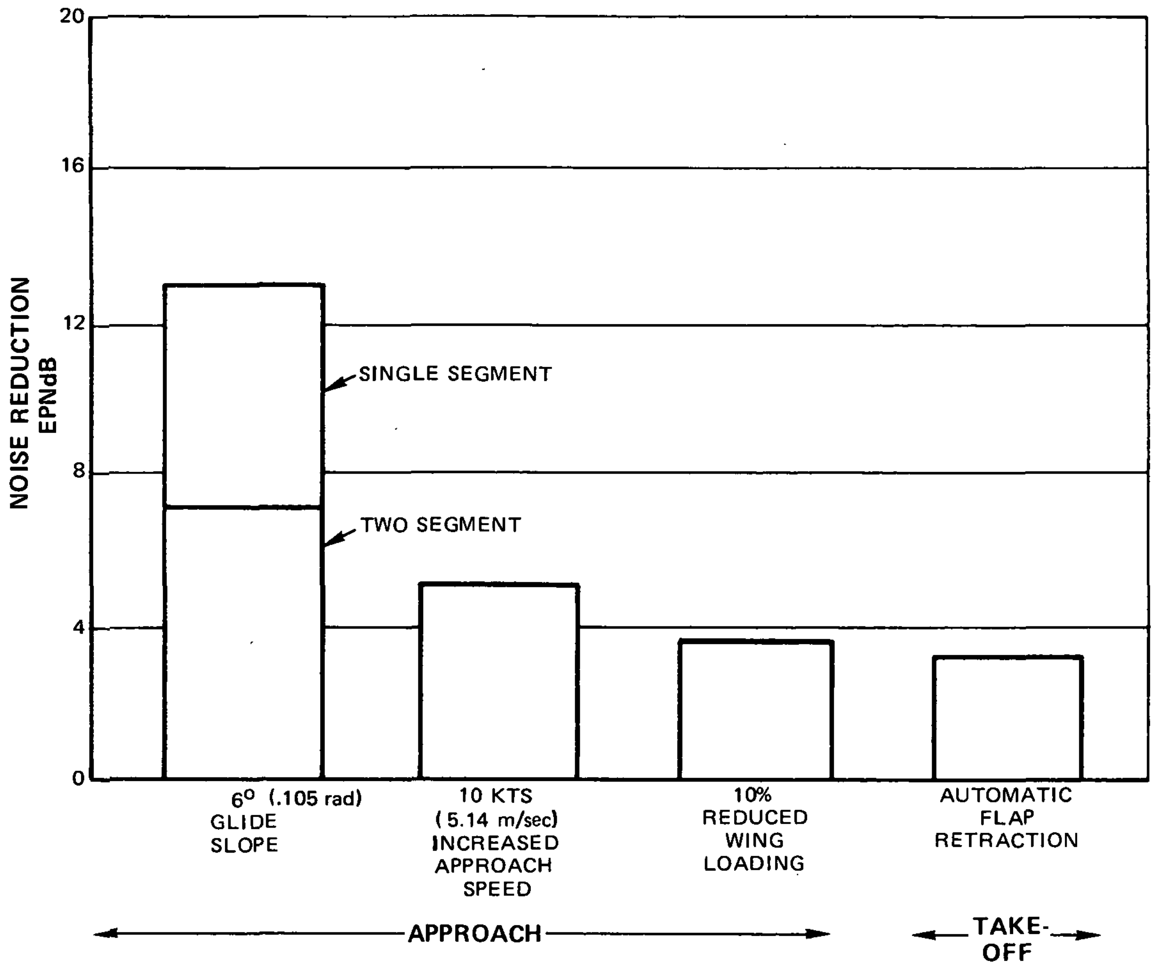

Figure 11 - Noise Reduction Summary

EMISSIONS

Expected exhaust emission levels of nitric oxide (NO), carbon monoxide (CO), unburned hydrocarbons and smoke were estimated for the STF429 and STF433 engines. Table VIII shows the ATT emission goals and the levels estimated for the study engines at the sea level conditions of ground idle and hot day (90°F) (305.5K) maximum take-off power. Except for smoke, which is expressed as SAE 1179 smoke number, the emission levels are in weight unit of emission type per 1000 weight units of fuel. No visible smoke is produced at any of those power settings. Both CO and unburned HC levels are lower than the goals. Although the NO level at maximum power is approximately half that of current technology burners, the NO goal of three is not met. To further reduce NO levels, water injection at the rate of 0.8 lbm (.36 kg) of water per lbm (kg) of fuel will reduce the peak flame temperature to meet the goal.

TABLE VIII

ATT ENGINE EMISSION ESTIMATES[1]

Emission Type	Engine Condition	ATT Goals	STF429	STF433
CO	Idle	40	Less than 30.0	Less than 30.0
Unburned HC	Idle	8	Less than 5.0	Less than 5.0
Smoke[2]	Takeoff	15	Less than 15	Less than 15
NO	Takeoff No water injection	3	12	Less than 12
NO	Takeoff 0.80 lb H_2O/lb fuel (0.36 kg H_2O/kg fuel)	3	3	3

(1) Numbers expressed as weight unit of emissions per 1000 weight units of fuel
(2) SAE 1179 smoke number

SYSTEM EVALUATION

Systems evaluation results for the STF429 and STF433 engines at the 3000 N.Mi(5556 km.) design range are shown in Figures 12 and 13. Three noise treatment configurations were evaluated: an untreated nacelle, an acoustically lined nacelle, and an acoustically lined wall combined with two inlet rings and one fan duct splitter.

For the STF429 engine, the increase in gross weight, direct operating cost (DOC) and reduction in return on investment (ROI) resulting from the use of maximum nacelle acoustic treatment are on the order of 6 percent in gross weight, 5 percent in DOC and -2.5 Δ percent in ROI. The STF433, which is designed for 5 EPNdB lower noise levels than the STF429, incurs further penalties of about 5 percent in gross weight, 4 percent in DOC and -2 Δ percent in ROI.

A comparison of the STF429 and the STF433 engines was also made in a 5500 N. Mi (10,200 km.) design range airplane (Figures 14 and 15). The longer range aircraft is more sensitive to the pressure losses in the inlet and fan exit duct from the addition of acoustic treatment than is the shorter range aircraft. The addition of full acoustic treatment to the STF429 results in a gross weight increase of approximately 8 percent, a 6 percent DOC increase and an ROI difference of -3 Δ percent. To obtain the lower noise of the STF433 requires additional penalties of 11 percent gross weight, 10 percent DOC and -3.5 Δ percent ROI.

It should be noted that the STF429 and STF433 represent different certification dates and levels of advanced technology. The lines connecting the two engines on Figures 12 through 15 are only intended to indicate trends with increasing bypass ratio and decreasing noise. If the STF433 represented 1979 technology rather than 1985, the trends would be even steeper.

CRUISE MACH NUMBER STUDY

Studies were conducted to determine the effect on aircraft system economics of using design cruise Mach numbers from 0.85 to 0.98. Four aircraft were studied which had design cruise speeds of .85, .90, .95 and .98. The Mach .85 and .90 aircraft utilized a conventional straight fuselage, whereas, the use of fuselage area ruling in conjunction with a wing glove was required for the Mach .95 and .98 aircraft. The engine used for these studies was the STF429 with full acoustic treatment. The results of the study are shown in Figure 16 in terms of design gross weight, direct operating cost and return-on-investment. The increasing trend in design gross weight with design cruise speed is caused by increased drag, higher fuel consumption and the larger airframe weight of a contoured fuselage all of which are associated with progressively higher Mach numbers. The block speed increase gained as cruise Mach number increases results in improved direct operating cost and return-on-investment up to a Mach number of 0.92 at which point the increased airplane cost due to the increased aircraft size overcomes the effect of the improved block speed.

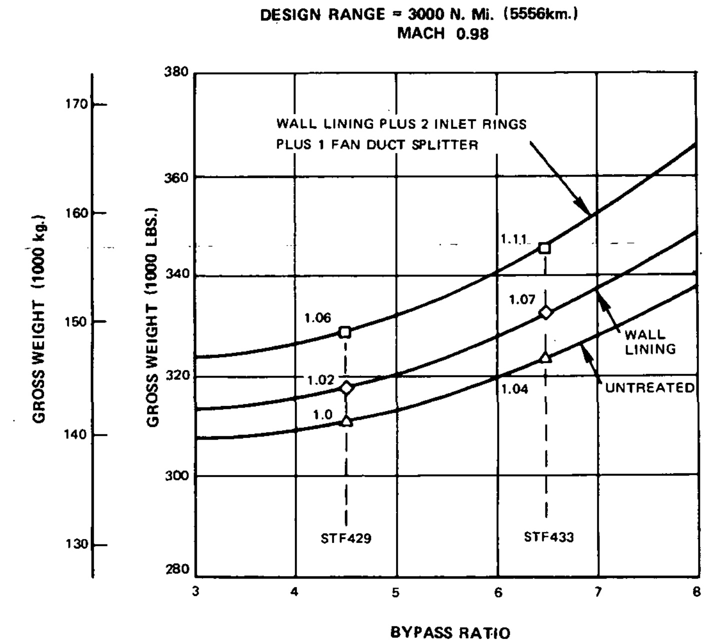

Figure 12 - Gross Weight Comparison for 3000 Nautical Mile (5556 km) Range

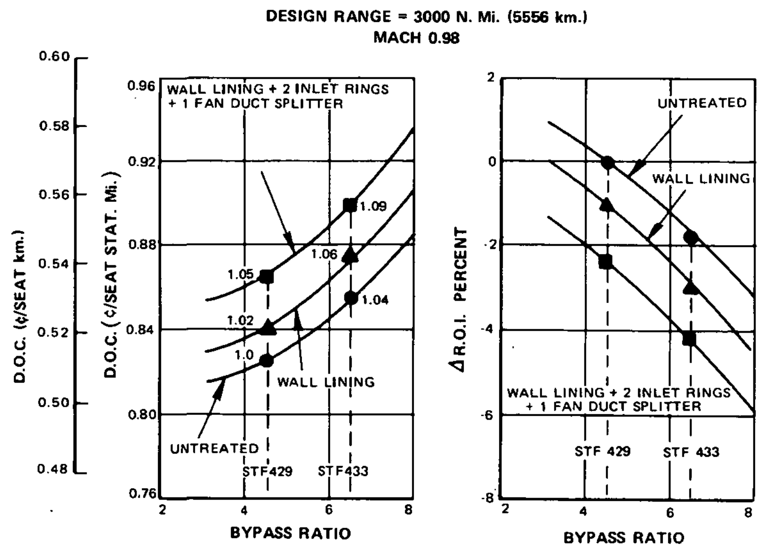

Figure 13 - Economic Comparison for 3000 Nautical Mile (5556 km) Range

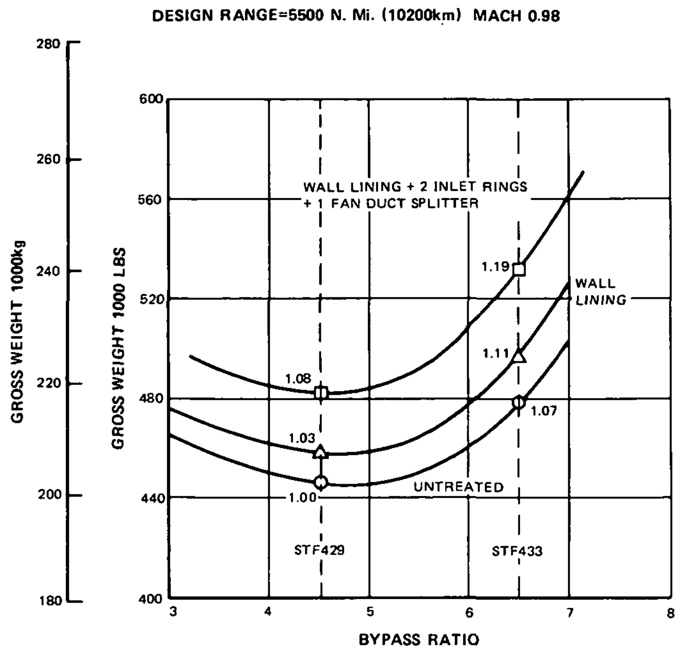

Figure 14 - Gross Weight Comparison for 5500 Nautical Mile (10200 km) Range

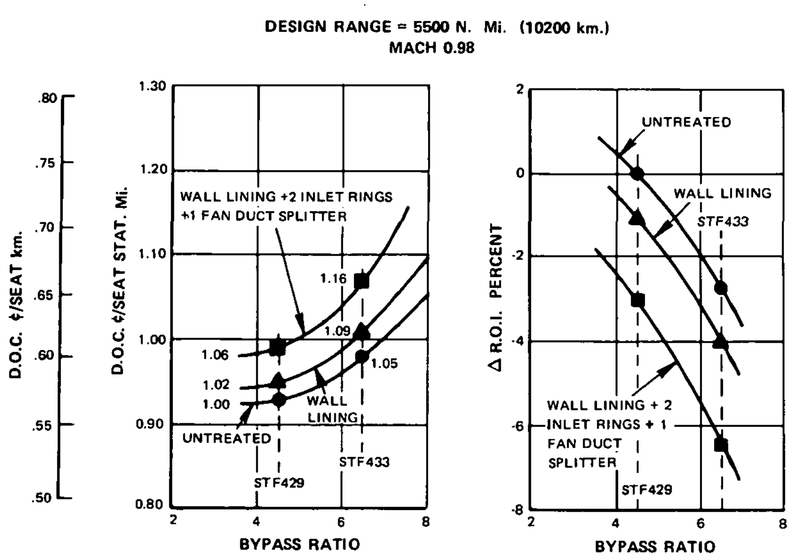

Figure 15 - Economic Comparison for 5500 Nautical Mile (10200 km) Range

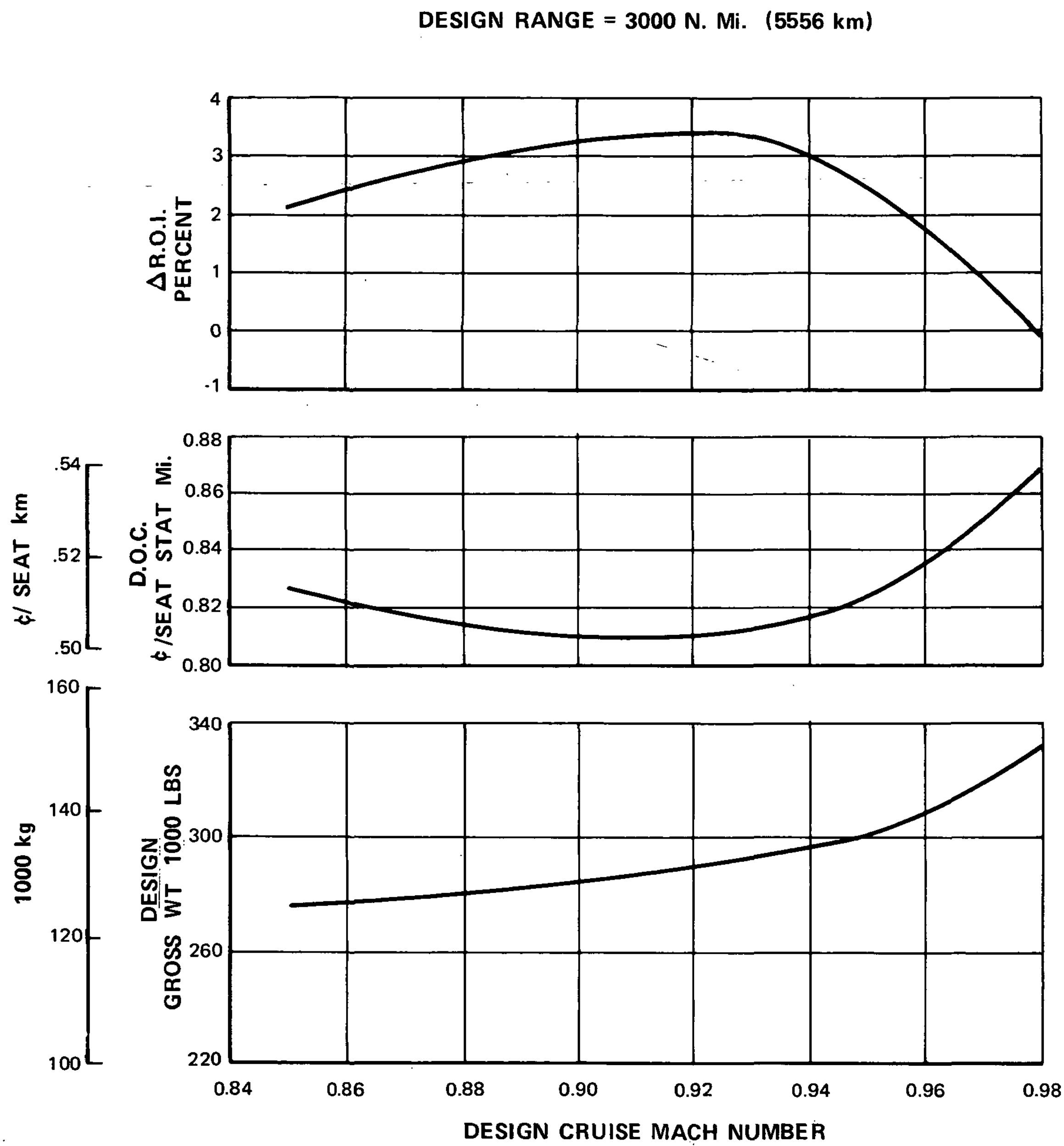

Figure 16 - Effect of Various Cruise Mach Numbers on Aircraft System Economics

IMPACT OF ADVANCED TECHNOLOGY

The two study engines incorporate the best combination of cycle and component configurations for a near-sonic, long-range transport, consistent with meeting higher environmental standards than are required for current engines. However, these environmental improvements impose certain penalties on the aircraft system. For example, to meet the noise goals, the selected bypass ratios are higher than the optimum range of three to four. Also, to achieve lower NO exhaust levels, the overall pressure ratio of 25 is lower than the optimum level of 30. The advanced technology postulated for each engine improves their environmental characteristics and helps to offset compromises to the engine cycles.

Table IX shows the overall economic benefits of some of the advanced materials and component technology that were projected for these ATT engines. These improvements are relative to current technology which is capable of doing the same job but with lower performance and increased weight and cost. The 1979 column lists the benefits of technology incorporated in the STF429 engine. The 1985 column shows the results of further technology advancements that were projected for the STF433 engine and are shown relative to current technology.

TABLE IX

BENEFITS FROM ADVANCED TECHNOLOGY

	Δ PERCENT R01	
	1979	1985
Composite Fan Blades	0.7	0.8
High Strength Disk Material	0.1	0.1
High Compressor/Turbine	0.1	0.8
Turbine Vane And Blade Materials		
TD Cobalt/Eutectic	2.0	–
Ceramic/Eutectic	–	3.8
Low Pressure Turbine	0.9	1.1
Total Δ Percent R0I	+3.8	+6.6

Graphite epoxy composite fan blades are lighter in weight than titanium blades and can achieve adequate flutter and resonance margins by using shroudless low aspect ratio (length/chord) designs. Titanium fan blades must retain a shroud because of the basically poorer modulus/density ratio of metal. The lighter composite blades permit reduced fan rotor and containment case weights and further, allow a reduction in the static structure required to support flight maneuver loads and possible blade loss loads. In addition, the elimination of shrouds improves the basic fan performance. As shown in Table IX, significant improvements from composite fan blades are projected for both the 1979 and 1985 engines.

Development of improved disk materials will result in lower engine weight. Improvements in the ductility and yield strength of titanium used in fan rotor and low temperature compressor disks can be achieved by chemical modifications. Improving the creep strength of titanium alloy by means of solid solution strengthening agents will allow the use of this lightweight material for the higher temperature stages of the compressor in place of nickel alloy disks. Highly alloyed nickel base materials now used in high temperature turbine disk applications can be significantly improved by powder metallurgy techniques and by thermo-mechanical working. These material benefits apply to both the 1979 and 1985 engines. Because the 1985 engine has a higher bypass ratio (and a smaller, more advanced high spool), the benefits from more advanced disk materials provide basically the same delta (Δ) percent ROI as for the 1979 engine.

Increased rotational speeds and the associated use of advanced compressor and turbine aerodynamic designs will provide more compact and lighter engines which will improve vehicle economics. The resulting economic benefits shown in Table IX are measured relative to current aerodynamic technology, speeds and mechanical configurations.

Development of advanced, high temperature materials and coatings for high pressure turbine blades and vanes will significantly reduce the cooling air requirements of future engines and thereby improve performance of the basic cycle. Also, cooling air has an adverse effect on turbine efficiency due to boundary layer distortion and inertia effects, and reduced cooling flows will improve the efficiency of the high pressure turbine. The material projections for 1979 include development of dispersion-strengthened cobalt alloy vanes with an advanced CoCrAlY coating and directionally solidified eutectic blades with an advanced NiCrAlY coating. The 1985 projections anticipate development of an uncooled ceramic vane material which does not require a separate protective coating and a more advanced eutectic/coating combination for blades. Because of the interdependence of advanced turbine materials with the airfoil cooling system, the benefits listed in Table IX are also dependent on the parallel development of advanced cooling methods (multi-hole, film cooling).

The last item in Table IX shows the benefits derived from a highly loaded, low speed turbine that compliments the low noise fan. This aerodynamic turbine technology will provide a high efficiency without imposing an excessive number of fan drive turbine stages. The benefit shown is based on the elimination of additional turbine stages which would be required if current turbine technology is applied.

In total, these advanced technologies offer a very significant improvement in economic potential to the airlines while meeting the environmental goals established for the 1980's. Without these advanced technologies, not only would the environmental goals be affected, but the gross weight and economic characteristics shown in the previous sections would not be attained.

TASK III

The Task III effort consisted of reviewing the technology implications of the two engines designed during Task II and making specific recommendations to NASA regarding the areas of new technology programs which should be pursued to best support the future development of improved long-range transports. The recommended efforts which are listed in Table X fall into one of two categories: engine component or systems design and improvements in materials. Within each grouping, individual programs are discussed in estimated order of importance. All programs, however, are important in terms of the role that each could play in improving the next generation of transport aircraft.

TABLE X

ADVANCED TECHNOLOGY PROGRAMS

COMPONENT AND SYSTEMS PROGRAMS

I. Evaluation of Noise and Performance Characteristics of a Spaced Two-Stage Fan

II. Highly Loaded, Low Speed Turbine Program

III. Integrated Engine/Nacelle Design and Powered Simulator Program

IV. Advanced Engine Control System Study Program

V. Application of Variable Geometry for Noise Reduction

VI. Low Emission Burner Program

MATERIALS PROGRAMS

I. Graphite/Epoxy for Fan Blade Applications

II. Ceramic Development for High Temperature Applications

III. Dispersion Strengthened Cobalt Turbine Vane Development Program

IV. Advanced Coating Development for Dispersion Strengthened Cobalt Vane Alloys

V. Directionally Solidified Eutectic Turbine Development Program

VI. Advanced Coating Development for Directionally Solidified Eutectic Alloy Blades

VII. Advanced High Pressure Turbine Disk Materials

VIII. High Yield Strength Titanium Fan/Compressor Disk Development

IX. High Creep Strength Titanium Compressor Disk Development

COMPONENT AND SYSTEMS PROGRAMS

I. <u>Low Tip Speed Fan</u> – The availability of a low tip speed, spaced two-stage fan is particularly crucial to achieving low noise goals with minimum system penalty. The practical use of this design requires investigating the inter-relationship between axial spacing of blades; numbers of blades and vanes; and the efficient use of localized acoustic treatment material.

A recommended program consists of the aerodynamic performance and noise testing of a scale model fan to optimize the design variables followed by verification testing of a full-sized fan on a demonstrator engine.

II. Low Speed Turbine – The low-noise two-stage fan requires a highly loaded, low speed turbine to drive it. Current turbine technology requires six to eight stages to be used to drive this type of fan or a large diameter turbine with fewer stages must be used. Either design approach results in significant cost, weight and installation penalties. New technology is needed to design a very low velocity ratio, high efficiency turbine. The use of sophisticated aerodynamic analysis systems coupled with studies of boundary layer flow behaviour should improve turbine efficiency by allowing a more precise airfoil contour design. The evaluation of high lift airfoil designs such as tandem airfoils and jet-flaps are expected to yield high aerodynamic blade loading. A program consisting of velocity diagram studies, blade channel layouts and airfoil experimental investigations in cascade and turbine rig apparatus is required, followed by testing of complete turbine units.

III. Integrated Nacelle – As cruise speeds approach Mach 1, increasing emphasis must be placed on designing low drag nacelles which are aerodynamically integrated with the airframe through area ruling. Achieving both low drag and low noise with these nacelles is a major design challenge. A two-pronged attack on this problem is recommended. The first is an integrated engine/nacelle design study which would examine all integration aspects required in realistic propulsion pods. The second concurrent effort would center on a powered simulator program in which various design configurations would be tested by means of a powered nacelle in a transonic wind tunnel. Each part of the program would provide data to the other and, through a process of design iteration, lead to a realistic evaluation of the problems of integrating acoustic rings and splitters, accessories, reversers and variable geometry features into an optimum aerodynamic nacelle configuration.

IV. Advanced Controls – Current commercial aircraft engines generally use self-contained hydromechanical control systems to maintain the engine within prescribed operating limits. Thrust settings, engine matching tasks, etc., are left to the flight crew. The new engines and airplanes under study will need improved control systems to meet the demands for accurate and continuous noise and emission control, flight path control, variable engine geometry control and maintenance of engine operating limits. A study of these control system needs is recommended. The extensive use of electronic computation for engine health analysis, data acquisition, navigation and aircraft system operation appears to provide a logical basis for an integrated control system. Improvements in accessory packaging can be especially useful in high speed aircraft if they result in reducing engine frontal area.

V. Variable Engine Geometry – Reductions in engine noise are usually achieved by increasing bypass ratio. This approach results in increasing the engine diameter which, unfortunately, causes increased airplane drag, especially when cruise speeds approach Mach 1.0. If variable turbine stators were used together with a variable primary exhaust nozzle it would be possible to completely control the power level and work of the turbine. This ability offers the possibility of directly reducing engine noise. These devices could also improve engine control and response time and thereby increase the feasibility of noise abatement procedures through flight trajectory modification. An analytical study program is recommended to investigate the engine matching and noise inter-relationships that can be achieved by using variable geometry exhaust nozzles, turbines, compressors and fans as well as compressor and turbine bleed systems.

VI. Low Emission Burner – A low emission main burner was used in the study engines to significantly reduce major exhaust emissions. The burner concept uses a dual operating system in attacking the problems of reducing both high and low power emissions without sacrificing burner performance, altitude relight or burner modulation capability. A program is recommended to establish the necessary technology base for this burner. It should begin with analytical studies and flow visualization tests. Promising configurations should then be experimentally evaluated using single flameholder element tests followed by a segmental rig test.

MATERIALS DEVELOPMENT

I. Composites – Graphite/epoxy composite material offers significant weight reduction possibilities for the spaced, two-stage fan. Although the behaviour of this material is excellent under fatigue loading, little data exist on its performance under combined tensile and fatigue loadings. Also its resistance to operational hazards such as humidity, erosion and foreign object damage remains unproven. A two phase program is recommended to investigate these problems. The first would evaluate the strength and fatigue properties of sample specimens using test laboratory techniques. The other phase would consist of fabricating and testing a full set of blades to determine aerodynamic performance and damage absorbing capability of the composite.

II. Ceramics – Ceramic materials hold considerable promise for turbine vane airfoils because of their ability to withstand high temperatures. Since these materials are not as ductile as metals, it is very important to be able to accurately predict localized maximum stresses in the airfoils. A program is recommended which identifies promising ceramic compositions by first developing fabrication methods for them through the use of materials laboratory tests and then experimentally verifying their durability by testing them in actual gas turbine engines. This materials development effort should be augmented by a program to develop improved analytical stress analysis methods for turbine airfoils.

III. Cobalt-base Alloys – Thoria dispersion strengthened (TD) cobalt-base materials have demonstrated superior high temperature strength potential over other superalloy turbine vane materials. This improved temperature capability reduces turbine cooling air requirements which results in significant engine performance increases. A program aimed at solving several recognized problem areas is recommended. Development efforts are needed to improve the stability and adherence of protective coating and to increase strength without sacrificing corrosion resistance. Optimization of airfoil extrusion parameters and methods should also be studied. A fabrication process is needed to attach mounting platforms to the extruded airfoil sections. Laboratory developed improvements should be verified by testing in both high pressure cascade rigs and in actual operating engines.

IV. Turbine Vane Coatings – An advanced coating material is needed to protect the TD cobalt-base alloy turbine vane material from corrosion. An improved CoCrAlY coating is needed which overcomes the shortcoming of current CoCrAlY coatings involving the loss of the principal protective element, aluminum, during operation. Development effort should investigate methods for improving the diffusional stability of the coating and for improving its oxidation resistance. Particular attention should be given to the problem of coating the small cooling air holes used in turbine vanes. Results of laboratory tests should be verified by testing sample vanes in a demonstrator engine.

V. Eutectic Turbine Blade Material – Directionally solidified eutectic alloys have shown considerable potential for increasing the strength and high temperature capability of turbine blades. These improvements reduce cooling air needs, thereby greatly reducing performance losses. A three step program is recommended for developing these alloys. The first step should investigate modification of the composition of existing alloys to improve mechanical properties. Directional solidification process development should be performed concurrently with the alloy formulation effort. The second step should establish allowable design levels for the best step one alloy and investigate root attachment methods. Step three would include testing a full set of eutectic blades in a demonstrator engine.

VI. Turbine Blade Coating – Improved coatings are also needed for these turbine blade eutectic alloys. Contemporary coatings are unacceptable for the high temperatures projected for eutectic blades and current coating methods do not protect the internal cooling passages in the blade. A four phase program is recommended to solve these shortcomings. During phase one a number of coating compositions should be screened using protection ability, ductility and fatigue crack resistance as the primary selection criteria. Evaluation of the internal coating potential of alloys would comprise the phase two effort. This would be followed (phase three) by testing of selected coatings on sample blades in a simulated engine environment. In phase four, actual in-engine testing would be used to select the best coatings.

VII. Turbine Disk Materials – The combination of increased turbine speeds and higher operating temperatures, which are used to improve engine performance, emphasize the need for improved turbine disk materials. Available data indicate that the properties of the currently used highly alloyed nickel-base disk materials can be improved if disks are made using powder metallurgy techniques. Also, advancements in thermo-mechanical working technology and inertia bonding have made possible disk design levels not previously considered practical. The investigation of these advanced turbine disk fabrication methods is recommended. Candidate materials should be screened for their thermo-mechanical workability and the mechanical properties of likely alloys determined. Inertia-bonding studies should be performed on the selected alloys. The best materials should then be fabricated into full size turbine disks and their adequacy experimentally verified.

VIII. Compressor Disks – High strength titanium alloys are needed to achieve the engine weight reduction attendant to high speed compressor designs. The alloy Ti6Al-2Sn-4Zn-6Mo demonstrates good low cycle fatigue properties but its low fracture toughness requires improvement. A program is recommended in which this basic titanium alloy is improved by chemistry modifications to achieve higher ductility at high strength and fracture toughness levels. Improved heat treatment techniques in conjunction with alloying constituents or methods for stabilizing the alloy should be investigated.

IX. High Creep Strength Titanium – The ATT engines require improved high temperature disk and blade alloys to reduce the weight of the high compressor. Substituting high creep strength titanium alloys for the heavy nickel base alloys which are now commonly used results in a considerable engine weight saving. Preliminary work indicates that the creep strength of titanium alloys can be significantly improved by chemistry and processing modifications. A program is recommended in which 1) alloy chemistry modification, 2) process modification for microstructure control, and 3) dispersion strengthening approaches are applied to the most promising titanium alloys in an attempt to improve their mechanical properties.

CONCLUSIONS

Recognizing the vital part that the long-range transport plays in world commerce, NASA is studying the application of advanced technologies to the next generation of long-range transports to assure that future designs will be fully responseive to national needs. This report describes propulsion system studies performed under direction of the Lewis Research Center to support this overall objective.

Extensive parametric engine cycle studies were performed to optimize the propulsion system for an Advanced Technology Transport (ATT) planned for commercial operation in the 1980's. Two major design criteria considered were low noise and low emission levels. The engine cycle selected is a twin spool turbofan with a low tip speed, widely spaced two-stage fan that provides both low noise and optimum cycle performance.

The noise goals of FAR Part 36 minus 10 EPNdB for 1979 commercial service and FAR Part 36 minus 15 EPNdB for 1985 can be met with cycles utilizing the low tip speed, spaced two-stage fan in combination with extensive advanced acoustic treatment in the nacelle. Two circumferential acoustic rings are required in the inlet and one circumferential acoustic splitter is required in the fan exit duct.

The two-stage fan offers the lowest noise potential with low tip speed and low fan pressure ratio per stage. In addition, optimum cycle performance is obtained by generating the high overall fan pressure ratio required for low cruise fuel consumption at a low tip speed with a high fan efficiency.

Operating procedures for noise abatement during approach and climb-out after take-off offer important noise reduction potential. As engine noise is reduced to these low levels, airframe generated noise from extended flaps and landing gear may become controlling.

The advanced premix, two zone, staged combustor reduces all emissions significantly. Carbon monoxide, unburned hydrocarbons and smoke levels are below the contract goals. Nitric oxide levels have been reduced by one-half from the level of today's high pressure ratio engines, but the engine still requires some water injection to meet the contract goal.

LIST OF SYMBOLS

A	Area, ft^2, m^2
BPR	Bypass Ratio
CET	Combustor Exit Temperature, °F, K
DOC	Direct Operating Cost; Direct airplane costs, including flying operation, direct maintenance (with burden) and flight equipment depreciation as defined in the Civil Aeronautics Board (CAB) Uniform System of Accounts and Reports.
EPNL	Effective Perceived Noise Level, EPNdB
FAR	Federal Aviation Regulations
FPR	Fan Pressure Ratio
IOC	Indirect Operating Costs; other CAB recognized airplane operating costs not included in DOC.
OASPL	Over-all Sound Pressure Level
OPR	Overall Fan-Compressor Pressure Ratio
ROI	Return-On-Investment; After-tax annual return on total investment in flight equipment plus related spares, based on a discounted cash flow analysis.
STF	Study Turbofan
TD	Thoria Dispersion
ρ	Density, lbm/ft^3, Kg/m^3

ELEMENTS

Al	Aluminum
Co	Cobalt
Cr	Chromium
Mo	Molybdenum
Sn	Tin

Ti	Titanium
Y	Yttrium
Zn	Zinc
COMPOUNDS	
HC	Hydrocarbons
NO	Nitric Oxide
CO	Carbon Monoxide

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